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Computed tomography of the abdomen of calves during the first 105 days of life: I. Reticulum, rumen, omasum and abomasum

Braun, Ueli ; Schnetzler, C ; Augsburger, Heinz ; Müller, U ; Dicht, S ; Ohlerth, Stefanie

Abstract: Computed tomographic (CT) images of the reticulum, rumen, omasum and abomasum of five healthy Holstein-Friesian bull calves were compared with anatomical transverse cadaver sections of the same calves. The calves were scanned in the transverse plane from the 5th thoracic vertebra to the sacrum six times three weeks apart from birth to 105 days of age. Multiplanar reconstruction was used to create images in sagittal and dorsal planes. After subjective assessment of various anatomical structures, the rumen, omasum and abomasum as well as the ruminal strata (gas cap, fibre mat and fluid phase) were measured. After the last CT scan, all calves were euthanised, and four were kept at -18 °C in sternal position for 14 days. Transverse sections 1.0 to 1.5 cm thick were made from two calves and dorsal and sagittal sections were made from one calf each using a band saw. The CT images and anatomical slices were compared and the structures on the CT images identified. Very clear CT images were obtained from the reticulum, rumen, omasum and abomasum and there was excellent agreement between images and anatomical slices.

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Computed tomography of the abdomen of calves during the first 105 days of life: I: Reticulum, rumen, omasum and abomasum

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Summary

Computed tomographic (CT) images of the reticulum, rumen, omasum and abomasum of five healthy Holstein-Friesian bull calves were compared with anatomical transverse cadaver sections of the same calves. The calves were scanned in the transverse plane from the 5th thoracic vertebra to the sacrum six times three weeks apart from birth to 105 days of age. Multiplanar reconstruction was used to create images in sagittal and dorsal planes. After subjective assessment of various anatomical structures, the rumen, omasum and abomasum as well as the ruminal strata (gas cap, fibre mat and fluid phase) were measured. After the last CT scan, all calves were euthanised, and four were kept at 18 °C in sternal position for 14 days. Transverse sections 1.0 to 1.5 cm thick were made from two calves and dorsal and sagittal sections were made from one calf each using a band saw. The CT images and anatomical slices were compared and the structures on the CT images identified. Very clear CT images were obtained from the reticulum, rumen, omasum and abomasum and there was excellent agreement between images and anatomical slices.

Keywords: computed tomography, cattle, calf, reticulum, rumen, omasum, abomasum

Computertomographie des Abdomens von Kälbern vom ersten bis zum 105. Lebenstag: I. Haube, Pansen, Psalter und Labmagen

In der vorliegenden Arbeit wurden die computertomographischen (CT) Befunde an Haube, Pansen, Psalter und Labmagen von 5 gesunden Kälbern von der Geburt bis zum Alter von 105 Tagen beschrieben und mit denjenigen der postmortalen Untersuchung verglichen. Die Kälber wurden in Abständen von 3 Wochen insgesamt 6 Mal computertomographisch untersucht. Die Untersuchung erfolgte in Transversalschnitten vom fünften Brustwirbel bis zum Sakrum. Mittels multiplanarer Rekonstruktion wurden die Strukturen auch in Sagittal- und Dorsalebene dargestellt. Im Anschluss

an die subjektive Beurteilung wurden verschiedene Strukturen, wie die Ausdehnung von Pansen, Psalter und Labmagen und diejenige der gasförmigen, flüssigen und festen Ingestaphase im Pansen bestimmt. Alle Kälber wurden im Anschluss an die CT-Untersuchung euthanasiert. Vier davon wurden während 14 Tagen bei -18 °C in sternaler Position tiefgefroren. Danach wurden 2 Kälber transversal in 1.0 bis 1.5 cm dicke Scheiben gesägt. Je ein Kalb wurde in Dorsal- bzw. Sagittalschnitten gesägt. Die Schnitte wurden den CT-Bildern der entsprechenden Lokalisation gegenübergestellt, um die abgebildeten Strukturen zu identifizieren. Haube, Pansen, Psalter und Labmagen konnten computertomographisch exakt dargestellt werden. Die Topographie der CT-Bilder und der anatomischen Schnittpräparate stimmten sehr gut überein.

Schlüsselwörter: Computertomographie, Rind, Kalb, Haube, Pansen, Psalter, Labmagen

Introduction

Disorders of the forestomachs and abomasum of calves, such as ruminal drinking syndrome, tympany, displaced abomasum and abomasal ulcers as well as other diseases, are commonly seen in practice (Dirksen, 2002; Radostits et al., 2007). A definitive diagnosis based on the results of clinical examination, haematological analysis, radiography and ultrasonography is not always feasible and further diagnostic techniques may be required. In human medicine, computed tomography (CT) has been shown to be an indispensable technique for diagnosis of abdominal diseases. It has also been used in small animal medicine for a number of years. Schnetzler (2012) reviewed numerous publications that extol the value of CT because it provides more information than radiography and ultrasonography. To our knowledge, there have been few studies on CT as an adjunctive diagnostic tool in cattle (Lee et al., 2009; Becker et al., 2011; Nuss et al., 2011). Because of their relatively small body size, calves are suitable for whole-body CT. To date, CT studies in calves have focussed mainly on diagnosis of central nervous system disorders (Lee et al., 2009), the use of a saline chaser to reduce the dose of contrast medium (Lee et al., 2010) and investigation of lung changes after experimental infection with *Mannheimia haemolytica* (Lubbers et al., 2007). Computed tomography has also been used to assess obstetrically relevant measurements in German Holstein-Friesian calves (Becker et al., 2011). Based on the usefulness of CT for the diagnosis of diseases in humans and small animals, we expected similar results in calves. Our goal was to examine five calves via CT every three weeks from birth to 105 days of age. During this period the rumen grows significantly and undergoes changes associated with the transition from a milk-based to mainly roughage diet.

Animals, Material and Methods

Animals

Five, clinically healthy, Holstein-Friesian bull calves were used. They were 24 to 48 hours (mean \pm sd = 34 ± 13 hours) old and weighed 47.9 ± 8.95 kg at the time of the first examination. The results of laboratory analyses were within normal reference ranges, and BVDV-antigen testing was negative.

Examination schedule

The calves underwent an initial CT scan during the first two days of life and then five more times three weeks apart for a total of six scans (days 1.4 ± 0.55 , 20.8 ± 1.10 , 41.8 ± 1.10 , 62.8 ± 1.10 , 83.8 ± 1.10 , 103.0 ± 2.35). Scans 1 to 4 were done approximately one hour after a milk feeding. After scan 4 (62 days), the diet was changed to hay. The calves were euthanised after the last scan and the findings of that scan were compared with postmortem findings.

CT examination and image processing

The animals were not fasted prior to anaesthesia, which was induced with midazolam (0.3 mg/kg) (Dormicum, Roche, Basle, Switzerland) and ketamine (3 mg/kg) (Narketan, Vetoquinol, Ittigen, Switzerland), and maintained with 2 - 2.5 % isoflurane (Forene, Abbott, Baar, Switzerland) delivered in oxygen through an endotracheal tube. The calves were scanned in sternal recumbency using a multidetector CT unit (Somatom Sensation Open, Siemens, Erlangen, Germany). Total scan time for the entire abdomen was 7 to 10 s. A detailed description can be found in the thesis published by Schnetzler (2012). Transverse slices, 5 mm in thickness, were taken from the fifth thoracic vertebra to the sacrum using 120 kV and 270 mA. The images were reconstructed to a thickness of 1.5 mm using a soft-tissue algorithm. Multiplanar reconstruction also allowed visualization of the structures in the sagittal and dorsal planes. The CT images were analysed using an image processing and analysis program (OsiriX Open Source™ 3.2.1 Syngo CT 2007S, OsiriX Foundation, Geneva, Switzerland). Soft tissue structures were assessed in a soft tissue window with a window width (W) of 400 Hounsfield Units (HU), and a window level (L) of 40 HU. The evaluation of the ruminal layering was carried out in an ingesta window (W 1200 HU/L 30 HU). After native images were completed, 2 ml/kg body weight contrast medium (Ultravist-370®, Bayer Schering Pharma, Zurich) was administered intravenously under pressure. The rate of injection corresponded to the scan time and was calculated as follows: Injection rate (ml/s) = (Total volume contrast medium for one patient (ml)/scan time (s)) + 10 s. The maximum volume of the bolus was 200 ml and the maximum rate of

injection was 6 ml/s. Abdominal images were taken 10 seconds apart at maximum expiration during apnoea to avoid respiratory-associated artefacts.

Measurements

After subjective assessment, various variables were measured in an appropriate window. The diameter of the oesophagus was measured perpendicularly to the longitudinal axis just cranial to the diaphragm. The maximum length, width and wall thickness of the reticulum were determined. The maximum length of the ruminoreticulum was measured in the sagittal or dorsal plane. The maximum height and width of the rumen were determined in the transverse plane. The thickness of the rumen wall was measured in the dorsal and ventral blind sacs medially at the level of the 2nd lumbar vertebra. The stratification of the rumen content was assessed in the transverse plane with ingesta window settings at the level of the maximum rumen height. This window position and width provided the best detail for differentiation of gas, liquid and solid phases of ingesta in the rumen. The size of the omasum was determined in the plane in which it could be best imaged and its wall thickness was measured without inclusion of the omasal leaves. The length of the abomasum was determined in the sagittal or dorsal plane and the width and wall thickness were measured in the transverse plane.

Euthanasia and postmortem section preparation

After the last CT scan, the calves were euthanized. Four were used for generation of transverse, sagittal and horizontal anatomical slices. They were placed in sternal recumbency in the same position used for the CT scans and kept at -18 °C for a minimum of 14 days. Transverse sections were obtained from two calves, which were cut along the longitudinal body axis into 1.0 to 1.5 cm slices using a bandsaw. One other calf was cut into 3 cm sagittal slices, and the fourth calf was cut into 3 cm horizontal slices. Depending on the sectioning plane, 20 to 93 sections were produced for each calf. A digital camera was used to record images of the transverse, sagittal and horizontal sections. The sections were compared with the corresponding CT images to accurately identify the structures. Labelling of anatomical structures and direct comparison of CT and digital images of sections were done using the program Paint.NET (Free software, www.getpaint.net) and Adobe Photoshop CS6 (Version 13.0.1, Adobe Systems GmbH, München, Germany).

Statistical analysis

The frequencies, means and standard deviations of the measured variables were calculated using the program SPSS (SPSS Statistics 20, IMB, Ehningen, Germany). Histograms and box-and-whisker plots were used for visual assessment of normality of distributions.

Results

The structures in the CT images could be accurately identified using the transverse, sagittal and horizontal anatomical sections (Fig. 1). Comparison of images taken with soft tissue and bone window settings and transverse anatomical sections at the level of each vertebra from the 5th thoracic vertebra to the sacrum has been previously reported (Schnetzler, 2012).

Reticulum, oesophageal groove and rumen

In the first scan, the reticulum and rumen were visible between the 9th thoracic and the 5th lumbar vertebra (Fig. 2). A marked increase in rumen size was apparent throughout the study. This was particularly evident after weaning when the diet changed from milk to roughage. By the end of the study, the rumen occupied the entire left hemiabdomen and extended to the sacrum. As a result, some of the other organs became displaced cranially and to the right.

The length of the reticulum and rumen in the first scan was 17.9 (\pm 1.69) cm (Fig. 3) and increased to 61.7 (\pm 4.60) cm by the 6th scan. The height of the rumen also increased markedly from 12.3 (\pm 2.51) cm in the first scan to 30.5 (\pm 2.15) cm in the last scan. The width of the rumen increased from 7.2 (\pm 0.92) cm in the first to 35.7 (\pm 1.58) cm in the last scan. The thickness of the rumen wall increased from 0.20 to 0.31 cm dorsally and from 0.23 to 0.33 cm ventrally.

The reticulum was located in the left paramedian region cranial to the rumen. It was adjacent to the lung craniodorsally, but the diaphragm between the two organs could not be imaged. The liver was to the right of the reticulum and the spleen to the left. The reticulum appeared circular to oval in transverse section (Fig. 4), and in newborn calves was filled with fluid. From the second scan onward, there was a ventral fluid phase and, similar to the rumen, a middle solid phase and a dorsal gas cap in the reticulum of most calves. The honeycomb structure of the reticular mucosa could be seen in the region of the gas cap and fluid phase. The thickness of the reticular wall was initially 0.18 to 0.21 cm (0.34 ± 0.21 cm) and did not change substantially during the study. The sagittal sections showed that a small area of the reticulum and heart was immediately adjacent to one another, separated only by the diaphragm (Fig. 5). The lungs were located dorsally, the abomasum caudally and the omasum caudodorsally.

The oesophageal groove could be seen in all calves in all scans (Fig. 6 A, B) and usually contained gas. It ran from the oesophagus along the inner surface of the medial reticular wall ventrally, where it joined the omasum at its ventral aspect and merged with the omasal groove. Initially, the rumen was small, fluid-filled and longitudinal and located caudodorsal to the reticulum. Its cranial aspect was in contact with the spleen and its caudal aspect touched the left abdominal wall. From the initial scan onward, the dorsal and ventral sacs were easily identified based on observation of the longitudinal groove in all of the calves. The cranial dorsal blind sac and caudal blind sacs, which are separated from the rest of the rumen by grooves, were not easily seen in all of the calves until the second scan (Fig. 7). Evaluation of the craniocaudal dimension of the rumen was easiest in the sagittal plane (Fig. 8). This plane yielded very good images of the transition from the reticulum to the cranial dorsal blind sac and the ventral sac of the rumen. The layering of the rumen contents was best seen using ingesta window settings. In the first scan, there was a distinct gas cap and a well-developed ventral fluid phase but no solid phase (Fig. 9 A). The height of the gas cap was an average of 2.8 (\pm 0.62) cm and that of the fluid phase 9.3 (\pm 2.71) cm (Fig. 10). The dorsal gas cap, middle fibre mat and ventral fluid phase were seen from the 2nd to 6th examination (Fig. 9 B). The fibre mat occupied most of the rumen followed by the gas cap and fluid phase. In the last scan, the gas cap composed an average of 15.7 %, the fibre mat 82.6 % and the fluid phase 1.7 % of the total height of the rumen.

Omasum

In the initial scan, the omasum was seen from the 12th thoracic to the 2nd lumbar vertebra (Fig. 11). As the rumen increased in size and the intestines developed, the omasum was displaced slightly cranially. The omasum also increased in size and by the 6th scan could be seen at the level of the 8th, 9th and 10th thoracic vertebrae in some of the calves. The omasum was very easily differentiated from the other forestomachs and abomasum because of its distinctive spherical appearance in transverse (Fig. 12) as well as in sagittal section (Fig. 13). The omasal leaves were seen as light grey septa, which projected from the omasal wall into the lumen. From the 4th scan, large and small leaves could be differentiated. The contents of the omasum consisted of fluid and gas in the first three scans, but changed to hypodense ingesta by the 4th scan.

The omasum was located dorsal to the reticulum between the rumen and the liver, on which it formed the omasal impression. The size of the omasum could best be determined in the sagittal and dorsal planes and was 6.4 (\pm 1.67) cm in the first scan and 15.9 (\pm 1.14) cm in the last (Fig. 14). The thickness of the omasal wall ranged from 0.23 (\pm 0.04) to 0.35 (\pm 0.28) cm regardless of age.

Abomasum

In the initial scan, the abomasum was seen from the 10th thoracic vertebra to the sacrum (Fig. 15) and was the largest of the four stomachs. Its length and width at this time were 30.9 (\pm 5.04) and 10.6 (\pm 2.24) cm, respectively (Fig. 16). The length of the abomasum did not vary during the study, but the width increased to 17.3 (\pm 1.16) cm, which was significantly different from the first scan ($P < 0.05$).

In the last scan, the abomasum was seen from the 8th thoracic to the 6th lumbar vertebra (Fig. 15). The thickness of the abomasal wall varied little throughout the study and was an average of 0.23 to 0.31 cm.

In the first scan, the abomasum sat on the abdominal floor and extended from the reticulum to the pelvic cavity (Fig. 17). The spleen was cranial and to the left and the rumen was caudal to the spleen to the left of the abomasum. On the right side, the liver was situated cranial to the abomasum and the intestines were caudal to the liver. The point where the pyloric region inclines dorsally and cranially was the caudal-most part of the organ in all scans. The pyloric part of the abomasum became narrower toward the pylorus and its orientation was at an acute angle with the body of the abomasum. The pylorus was readily seen in all scans and appeared round on the outside with an irregular star-shaped structure on the inside, which opened cranially into the thin-walled duodenum. The location of the abomasum and pylorus varied, sometimes markedly depending on the gas content. In the initial scan, the pylorus was usually on the right and dorsal, in the second scan, it was on the left and dorsal and in the third scan it was on the right and ventral. The abomasal mucosal folds were always seen and extended into the lumen as hyperdense structures compared with the ingesta. Irregular and hyperdense milk coagula were seen in the first two scans. At all examinations, fluid and a varying amount of gas were seen in the lumen. The abomasum was round in cross section in the first scan, but with an increase in the volume of the rumen, it narrowed and became displaced from the median to the right side.

Discussion

The main goal of this study was to describe the normal structure and position of the reticulum, rumen, omasum and abomasum using CT in calves from birth to 105 days of age. Normal values for the size and position of these organs were secondary goals. Correct interpretation of CT images requires a thorough understanding of cross-sectional anatomy. The normal CT findings including comparison of the images with corresponding anatomical slices have been reported in dogs (Teixera et al., 2007; Rivero et al., 2009), cats (Samii et al., 1998) and goats (Irmer, 2010; Braun et al., 2011a, b, c). The

anatomical slices were regarded as essential for identification and evaluation of abdominal structures in the CT images. Similar studies have not been carried out in calves. The contour of the reticulum and rumen was distinctly demarcated in the ingesta window because of the contrast between their walls and the luminal contents (gas, fluid and ingesta) and surrounding adipose tissue. The wall of these two organs was hyperdense and appeared light to medium grey on images. This was exemplified by the clear depiction of the characteristic honeycomb structure of the reticular mucosa. There was also a distinct contrast between the omasal wall and leaves and the markedly hypodense (black) ingesta seen in the ingesta window. Identification and evaluation of the layers of the rumen content were not possible with soft tissue window settings and thus, a special window width and level had to be selected. Window settings W1200 HU/ L30 HU, which were also used to evaluate rumen stratification in goats (Irmer, 2010; Braun et al., 2011a) were found to produce the best images. At present, CT is the only non-invasive method of reliably identifying and assessing rumen stratification in detail, and it is superior to ultrasonography for this purpose. Although ultrasonography can be used to differentiate the dorsal gas cap and middle fibre mat, it can only rarely identify the transition from the fibre mat to the ventral fluid phase (Gautschi, 2010; Braun et al., 2012). It is likely that the measurements of the ruminal layers do not correspond exactly to those in a standing animal because the calves were examined in sternal recumbency on the CT table, which probably caused some compression of the abdomen and ruminal distortion. Comparison of ruminal stratification in calves and goats was interesting. Similar to findings in goats, the largest vertical measurement was obtained from the fibre mat. However, by the 6th scan, a mean of 82.6 % of the rumen height was fibre mat in calves compared with 62.5 % in hay-fed goats (Irmer, 2010; Braun et al., 2011a). The second largest component was the gas cap (15.7 %) in calves and the fluid phase in goats (25.9 %). The fluid phase composed only 1.7 % of the rumen height in calves, and in goats the gas phase was the smallest component (11.1 %). These differences indicate that the composition of the rumen contents of calves and goats vary markedly. The very small fluid phase in the rumen of calves explains why the transition from the fibre mat to the fluid phase is difficult to identify ultrasonographically, whereas the transition from fibre mat to gas cap is easily seen (Gautschi, 2010; Braun et al., 2012). Other studies have also shown that the fibre mat extends far into the ventral sac of the rumen in cattle (Kovács et al., 1997; Ahvenjärvi et al., 2001; Hummel et al., 2009), which is likely why the fibre mat and fluid phase usually cannot be differentiated ultrasonographically in adult cattle (Tschuor and Clauss, 2008; Braun et al., 2013). In contrast to cattle and goats, browsing ruminants such as elk do not have a gas cap (Tschuor and Clauss, 2008) because the gas produced by fermentation is distributed within the ingesta. This imparts a frothy appearance to the rumen contents, which in cattle is

characteristic of frothy bloat. Stratification of ruminal contents is a diagnostic consideration in several conditions of the rumen. The gas cap occupies the majority of the rumen in cows with free gas bloat, and in ruminal acidosis, the contents become fluid. Changes in the size of the fibre mat are seen in rumen impaction. Stratification changed during the first 100 days of life. Rumen contents consisted of liquid and gas in the initial scan, after which the proportion of liquid decreased significantly within three weeks and continued to decrease afterwards. In contrast to CT studies in goats (Braun et al., 2011a), foreign bodies were not seen in the reticulum of any of the calves. The calves were young and the likelihood of a reticular foreign body was therefore small.

The omasum was seen on all CT images and was easily identified based on the characteristic appearance of the omasal leaves that projected into the lumen. This could also be seen on CT images in goats (Irmer, 2010; Braun et al. 2011a), whereas the omasal leaves could not be seen ultrasonographically in calves (Gautschi, 2010; Braun and Gautschi, 2012) or mature cows (Braun and Blessing, 2006). The only time when omasal leaves are seen ultrasonographically is with abomasal reflux in cows with ileus or displaced abomasum (Braun, 2009).

Although CT proved a useful imaging modality for the abomasum, we believe that ultrasonography is the better choice for examination of this organ. It allows real-time observation of dynamic abomasal processes that occur during ingestion and clotting of milk (Gautschi, 2010; Braun and Gautschi, 2012), which is not possible with CT. Determining abomasal size is also straightforward ultrasonographically.

The development of the forestomachs and the abomasum during the study was of great interest. The forestomachs increased significantly in size during the study, whereas the size of the abomasum changed little, in agreement with earlier reports in the literature (Nickel et al., 2004; König et al., 2005; Salomon et al., 2008; Schnorr and Kressin, 2011).

Anatomical cadaver sections were critical for the interpretation of CT images. They provided a clear illustration of topographical relationships between organs and their structural differences and allowed the identification of anatomical structures in CT images. The sagittal sections were of particular value for visualising and measuring organs in their longitudinal axis. Finally, CT imaging of the reticular groove in the calves of this study deserves mentioning. To our knowledge, this is the first account of the depiction and description of the exact course of the reticular groove from the oesophagus to the transition to the omasal groove using an imaging modality.

Conclusions

292 The results of this study provide a basis for CT examination of the forestomachs and abomasum of
293 calves during the first 105 days of life. Computed tomography appears to be a promising imaging
294 technique for refining the diagnosis of abdominal disorders in calves, thus allowing more specific
295 treatment.

296

297 **References**

298 See communication III.

299

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Legends to figures

Figure 1: Comparison of a transverse CT image in a soft-tissue window setting (A) and the corresponding anatomical slice (B) at the level of the 13th thoracic vertebra in a 105-day-old Holstein-Friesian bull calf. 1 Aorta, 2 Liver, 3 Caudal vena cava, 4 Portal vein, 5 Gallbladder, 6 Spleen, 7 Splenic vein, 8 Cranial dorsal blind sac of rumen, 9 Ventral sac of rumen, 10 Omasum, 11 Abomasum, 12 Pylorus, 13 Pancreas, R Right, L Left.

Figure 2: Visibility of the reticulum and rumen (ruminoreticulum) on transverse CT images in five Holstein-Friesian bull calves. The images were taken at different thoracic and lumbar vertebrae and the sacrum during six CT scans in the first 105 days of life. The different shades of red indicate the number of calves in which the organs were visible at the respective levels. 20 %, 40 %, 60 %, 80 % and 100 %, visible in 1, 2, 3, 4 and in all calves, respectively.

Figure 3: Length, height and width of the ruminoreticulum in five Holstein-Friesian bull calves during the first 105 days of life.

Figure 4: Transverse CT images of the reticulum at the level of the 10th thoracic vertebra in a two-day-old calf (A) and at the level of the 12th thoracic vertebra in a 105-day-old Holstein-Friesian bull calf (B). 1 Reticulum, 2 Caudal vena cava, 3 Lung, 4 Left lobe of liver, 5 Aorta, 6 Sternum, 7 Spleen, 8 Cranial dorsal blind sac of rumen, 9 Omasum, R Right, L Left.

Figure 5: Sagittal CT image of the reticulum at the level of the aorta in a two-day-old (A) and 105-day-old Holstein-Friesian bull calf (B). 1 Reticulum, 2 Heart, 3 Lung, 4 Aorta, 5 Left kidney, 6 Abomasum, 7 Oesophagus, 8 Cranial dorsal blind sac of rumen, 9 Ventral sac of rumen, 10 Dorsal sac of rumen, 11 Spleen, Cr Cranial, Cd Caudal.

Figure 6: Transverse CT image of the oesophageal groove at the level of the 9th thoracic vertebra in a 104-day-old Holstein-Friesian bull calf (A) and a sagittal CT image of the oesophageal groove at the level of the caudal vena cava in a 103-day-old calf. 1 Reticulum, 2 Oesophageal groove, 3 Cranial dorsal blind sac of rumen, 4 Rumen, 5 Omasum, 6 Abomasum, 7 Right kidney, 8 Left kidney, 9 Liver, 10 Caudal vena cava, R Right, L Left.

335 Figure 7: Dorsal CT images of the rumen at the level of the oesophagus in a two-day-old Holstein-
 336 Friesian bull calf (A) and at the level of the apex of the heart in a 105-day-old bull calf (B). 1
 337 Reticulum, 2 Cranial dorsal blind sac of rumen, 3 Rumen, 4 Caudodorsal blind sac of rumen, 5
 338 Caudodorsal blind sac of rumen, 6 Omasum, 7 Oesophagus, 8 Apex of heart, 9 Liver, 10 Spleen, 11
 339 Left kidney, R Right, L Left.
 340

341 Figure 8: Sagittal CT images of the abdomen in the left paramedian region of a one-day-old Holstein-
 342 Friesian bull calf (A) and at the level of the apex of the heart in a 105-day-old calf (B). The
 343 abomasum and reticulorumen dominate the abdominal cavity at the ages of one and 105 days,
 344 respectively. 1 Reticulum, 2 Cranial dorsal blind sac of rumen, 3 Ventral sac of rumen, 4 Dorsal sac
 345 of rumen, 5 Abomasum, 6 Spleen, 7 Heart, Cr Cranial, Cd Caudal.
 346

347 Figure 9: Transverse CT images of the abdomen at the level of the 2nd lumbar vertebra in a two-day-
 348 old Holstein-Friesian bull calf (A) and at the level of the 3rd lumbar vertebra in a 105-day-old calf (B)
 349 (ingesta window settings). The green lines show the height (a gas cap, b fibre mat, c fluid layer) and
 350 width (d) of the rumen. 1 Dorsal sac of rumen, 2 Ventral sac of rumen, 3 Lateral longitudinal groove,
 351 4 Medial longitudinal groove, R Right, L Left.
 352

353 Figure 10: Size of gas cap, fibre mat and fluid phase of the rumen in five Holstein-Friesian bull calves
 354 during the first 105 days of life.
 355

356 Figure 11: Visibility of the omasum on transverse CT images in five Holstein-Friesian bull calves.
 357 The images were taken at the level of different thoracic and lumbar vertebrae during six CT scans in
 358 the first 105 days of life. For colour key see Fig. 2.
 359

360 Figure 12: Transverse CT image of the omasum at the level of the 1st lumbar vertebra in a one-day-
 361 old Holstein-Friesian bull calf (A) and at the level of the 13th thoracic vertebra in a 105-day-old calf
 362 (B). 1 Omasum, 2 Rumen, 3 Abomasum, 4 Spleen, 5 Liver, R Right, L Left.
 363

364 Figure 13: Sagittal CT image of the omasum at the level of the caudal vena cava in a 105-day-old
 365 Holstein-Friesian bull calf. 1 Omasum, 2 Reticulum, 3 Rumen, 4 Abomasum, 5 Liver, 6 Caudal vena
 366 cava, 7 Lung, 8 Left kidney, Cr Cranial, Cd Caudal.
 367

368 Figure 14: Craniocaudal measurements of the omasum taken during six CT scans in the first 105 days
369 of life in five Holstein-Friesian bull calves.
370

371 Figure 15: Visibility of the abomasum on transverse CT images taken at different thoracic and lumbar
372 vertebrae and the sacrum (S) in five Holstein-Friesian bull calves. For colour key see Fig. 2.
373

374 Figure 16: Changes in length and width of the abomasum in five Holstein-Friesian bull calves during
375 the first 105 days of life.
376

377 Figure 17: Dorsal CT images of the abomasum at the level of the apex of the heart in a one-day-old
378 Holstein-Friesian bull calf (A) and at the level of the sternum in a 105-day-old calf (B). 1 Reticulum,
379 2 Abomasum, 3 Milk coagula, 4 Pylorus, 5 Descending part of duodenum, 6 Rumen, 7 Intestines, 8
380 Spleen, 9 Liver, R Right, L Left.